Object-Space Interference Detection on Programmable Graphics Hardware

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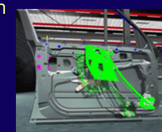
Motivation

- Collision detection is a fundamental task in
  - Virtual Prototyping
  - Haptic rendering (force-feedback)
  - Physically-based simulation (rigid bodies etc.)
  - Medical training/planning systems



- Collision detection performance is critical for
  - Responsive VR systems
  - Real-time simulation
  - Natural interaction

→ Need of hardware accelerated algorithms

Previous Work

- Collision detection in graphics hardware
  - image-space algorithms:
    - RECODE [Baciu et al. 1999]
    - CInDeR [Knott,Pai 2003]
    - CULLIDE [Govindaraju et al. 2003]

    and further image-space methods
  - → restricted to objects of certain shape and connectivity
- Hierarchical collision detection
  - OBBs [Gottschalk et al. 1996]
  - DOPs, AABBs [Zachmann 1998, 2002]
  - Convex surface decomposition [Ehmann et al. 2001]

Programmable Graphics Hardware (GPU)

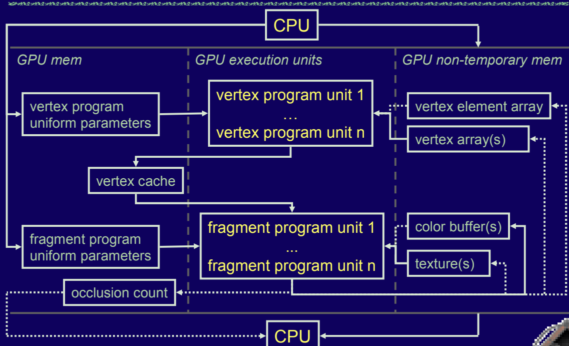
- parallel architecture of GPU:

  multiple *vertex program* / *fragment program* execution units
    - vertex and fragment programs are designed to run with an arbitrary number of execution units
    - → scalability to future GPUs
- all calculations in floating point

  (up to 32 bits precision)
- SIMD instruction set

→ high floating point throughput

GPU architecture overview

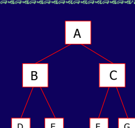


Our Goal

- Collision detection on current graphics hardware
  - using programmable graphics hardware (GPU)
  - utilizing its SIMD capabilities and high floating point throughput (using *floating point textures* for storage)
  - implementing an *hierarchical* algorithm
  - *exact* interference detection in *object-space*
  - no requirements on shape, topology, connectivity

Bounding Volume Tree

inner nodes: bounding volumes (*AABB*s in our approach)
leaf nodes: triangles



Simultaneous traversal of two trees:

- all pairs of nodes (S_i, T_i) are considered, where S_i is a node of tree *S* and T_i is a node of tree *T* on the same hierarchy level
- for a pair of inner nodes (S_i, T_i) their child nodes have to be checked only if the bounding volumes (BVs) corresponding to S_i and T_i overlap

Our traversal scheme:

- breadth-first strategy (to exploit parallelism)

Simultaneous overlap testing of multiple BVs

- Central task of the breadth-first traversal:
  given: *list L, tree node T*
  determine: *list of those nodes from L that overlap with T*

- Pseudocode:

```
overlappingChildren (list L, node T): list
list L';
for all nodes S from list L do
    for all children S_i of S do
        if S_i and T overlap then
            L'.append(S_i);
return L';
```

Simultaneous overlap testing of multiple BVs

- Idea: implement as fragment program
  - thereoretically, all overlap tests could be executed in parallel as they are independent of each other
  - parallel execution requires a data structure that allows direct access to elements (arrays); lists are unsuitable
  - arrays can be represented on the graphics hardware by (floating-point) textures

➔ make loop vectorizable by using arrays instead of lists

Simultaneous overlap testing of multiple BVs

Naïve approach: use arrays with NULL-elements

overlappingChildren (array *a*, node T): array

array *a'*;
for all nodes S_j from array *a* **do**
  for all children $S_{j,i}$ of S_j **do**
    if $S_{j,i}$ and T overlap **then**
      a' [2j+i] := $S_{j,i}$;
    else
      a' [2j+i] := NULL;
return *a'*;

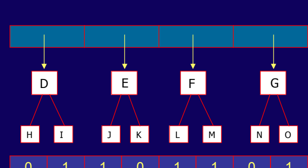
➔ vectorizable, but unsuitable for parallel execution by a fragment program where one execution unit is assigned for each output array element

Simultaneous overlap testing of multiple BVs

Solution: tightly-packed arrays

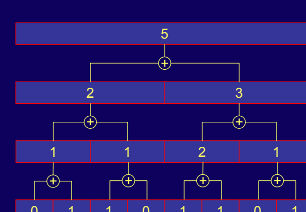
1. Calculate overlap counts for the children of all nodes contained in the input array
(i.e. 1 if there is an overlap, 0 otherwise)

input:



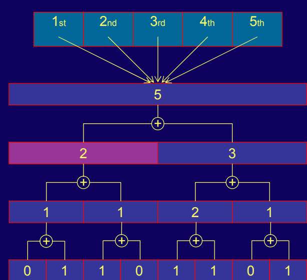
Simultaneous overlap testing of multiple BVs

2. Build a tree by summing up overlap counts
corresponds to a *mip-map*; total size *O(n)*



Simultaneous overlap testing of multiple BVs

3. Successively construct the output array



Simultaneous overlap testing of multiple BVs

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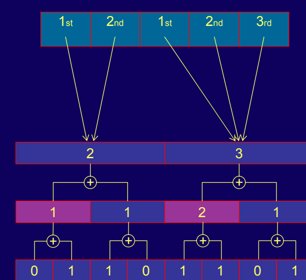

Simultaneous overlap testing of multiple BVs

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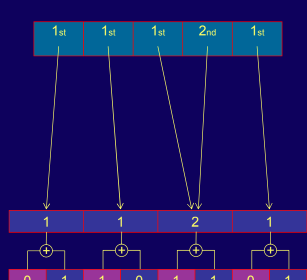

Simultaneous overlap testing of multiple BVs

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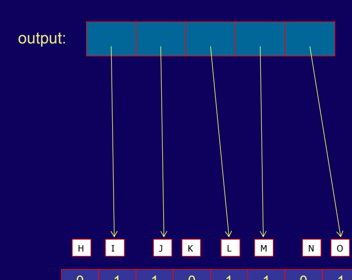
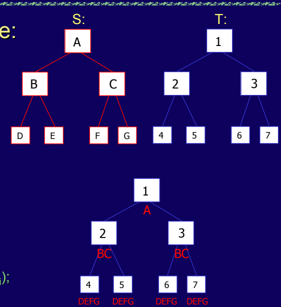


The overall simultaneous traversal scheme

- Pseudocode using a queue:

```
traverse (node S, node T):
queue q;
array a := { S };
q.insert(a, T);
while q is not empty do
{
    (a, T) := q.top;
    q.pop;
    for all children T_i of T do
    {
        array a' := overlappingChildren(a, T_i);
        q.append(a', T_i);
    }
}
```

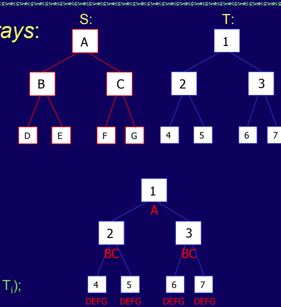


The overall simultaneous traversal scheme

- Pseudocode using *2D arrays*:

```
traverse (node S, node T):
array a := { S };
array b := { (a, T) };
while b is not empty do
    b := overlappingChildPairs(b);

overlappingChildPairs (array b): array
array b';
for all (a_j, T_j) from array b do
    for all children T_j,i of T_j do
    {
        array a_j' := overlappingChildren(a_j, T_i);
        b'[2j+i] := (a_j', T_i);
    }
return b';
```



The overall simultaneous traversal scheme

- Subroutine *overlappingChildPairs()*:
  - is vectorizable as an array is used for input/output and there are no other dependencies between iterations
  - its subroutine *overlappingChildren()* is – as described – executed by a fragment program

→ Idea: implement as vertex program
  - the input array can be specified using vertex array(s)
  - the output array must be written to vertex array(s), too

- requires the new *ARB_super_buffer* OpenGL extension

Implementation details

- Mapping of data structures to GPU memory:
  - one call of *overlappingChildPairs()* corresponds to rendering n lines of lengths $m_0 \dots m_{n-1}$ into a 2D buffer, where n is the length of array b and m_j is the length of array a_j
  - the nodes of tree S, which are referenced by the elements of arrays a_j, are stored in sets of 1D textures (up to three textures per hierarchy level)
  - the nodes of tree T, which are referenced by the elements of array b, are stored in vertex arrays (one per hierarchy level)
  - the lengths of the arrays a_j, which are determined inside the subroutine *overlappingChildren()*, are written to an additional vertex array (using *ARB_super_buffer* extension)
  - transformation matrixes for trees S and T can be passed to the fragment and vertex program units as program parameters

Implementation details

- Hardware limitations:
  - the number of nodes for each hierarchy level (and therefore the number of triangles of a single mesh) may not be larger than the max. allowed texture size *M* (usually *M*=2048)
  - → larger meshes have to be split into multiple sub-meshes with max. *M* triangles each
- Possible optimizations:
  - avoid unnecessary calls of *overlappingChildPairs()* when array *b* contains only empty arrays a_i (can be determined by querying an occlusion count using the *ARB_occlusion_query* extension)
  - by using 2D textures of height *M* for every hierarchy level *i* and packing multiple 2D arrays into these textures, $M/2^i$ meshes can be processed simultaneously by a single batch (i.e. a single *overlappingChildPairs()* call)

Conclusions and Future Work

- Summary:
  - hierarchical collision detection using programmable graphics hardware
  - all calculations done in object-space, not image-space
  - no requirements on shape, topology, connectivity
- Ongoing and future work:
  - in-depth performance analysis of our implementation
  - the usage of bounding volumes other than AABBs and of enhanced tree traversal schemes are to be evaluated

Questions?